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HPM Damage Thresholds of GaAs FETs and HEMTs

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Measurements are presented of the damage thresholds of low-noise gallium arsenide (GaAs) field-effect transistors (FETs) and high-electron-mobility transistors (HEMTs) when these devices are exposed to high-power microwave pulses. Because the devices measured have gate lengths of one-half micron or less, they represent the state of the art and thus provide a susceptibility database for receiver- and system-design engineers. As the devices were biased for low-noise operation at room temperature, most of these measurements simulated normal system operation. However, to determine the effects of temperature on the damage threshold, several measurements were made at -20 and 95°C. Also, measurements were made under different conditions of bias on the device and different frequency content of the microwave input (i.e., single and multiple tones), to determine the effect of these factors.

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I. INTRODUCTION

Front-end elements are vulnerable to HPM damage because they can be strongly coupled to incident HPM fields by the system's antenna. Low-noise amplifiers using GaAs FETs and HEMTs are increasingly replacing mixers as front-end elements to improve the noise figure of microwave receivers. The measurements presented here determine the damage threshold of low-noise GaAs FETs and HEMTs subjected to pulsed high-power microwaves, as well as the degree to which this damage degrades amplifier performance. Although the general physical characteristics of the damage occurring in these devices are presented, the physics underlying the burnout process was not investigated.

Several studies have reported the pulsed-microwave damage thresholds of GaAs FETs [1-6]. The peak pulse powers for burnout have usually been reported to be between 1 and 50 W, with the exception of McAdoo et al. [6], who reported some burnout thresholds in the hundreds of watts. The present study has three principal goals: (1) to extend the work of previous investigations by including a broader range of devices, including HEMTs and state-of-the-art GaAs FETs; (2) to investigate the influence on burnout threshold of several factors, including device temperature and bias and the frequency content of the incident microwave power; and (3) to investigate the reason for the anomalously high threshold powers reported in [6].

II. EXPERIMENTAL SETUP AND PROCEDURE

The setup for the microwave pulse measurements is indicated schematically in Figure 1. A photograph of the setup is shown in Figure 2. The pulse was formed by a PIN switch that modulated a cw Gunn oscillator. The measurements that employed pulses shorter than 100 ns used a PIN switch having 900-ps rise and fall times and a Gunn source at 6 GHz, but most of the 100-ns pulse measurements used a PIN switch having a 5-ns rise time and a 7-ns fall time, as well as a Gunn source at 8 GHz. The pulse from the PIN switch went through a step attenuator that allowed the power level to be varied, and then was amplified by a TWT amplifier to the power level appropriate for the burnout measurement. The pulse reflected from the device under test (DUT) was monitored by means of a directional coupler and a wide-band crystal detector, whose output was displayed on a fast-storage oscilloscope. Manually operated microwave switches placed before and after the DUT enabled the microwave pulses to be alternated with the gain and noise figure measurements of the DUT.

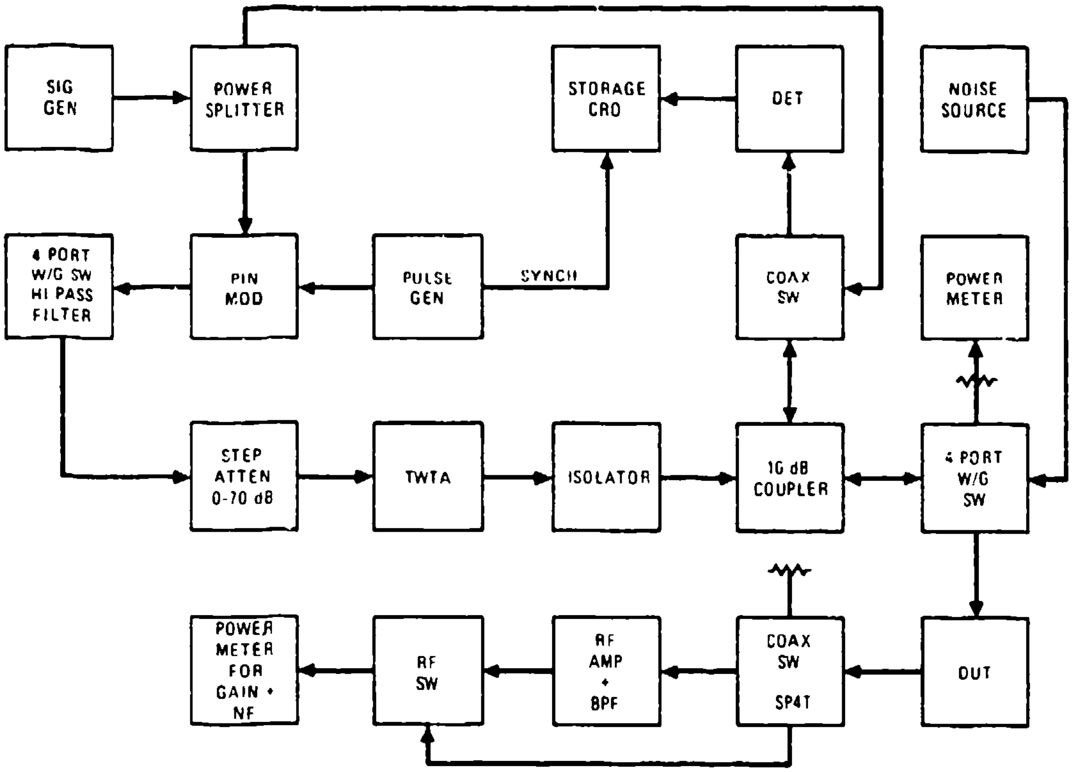

Figure 1. Schematic of the Measurement System.

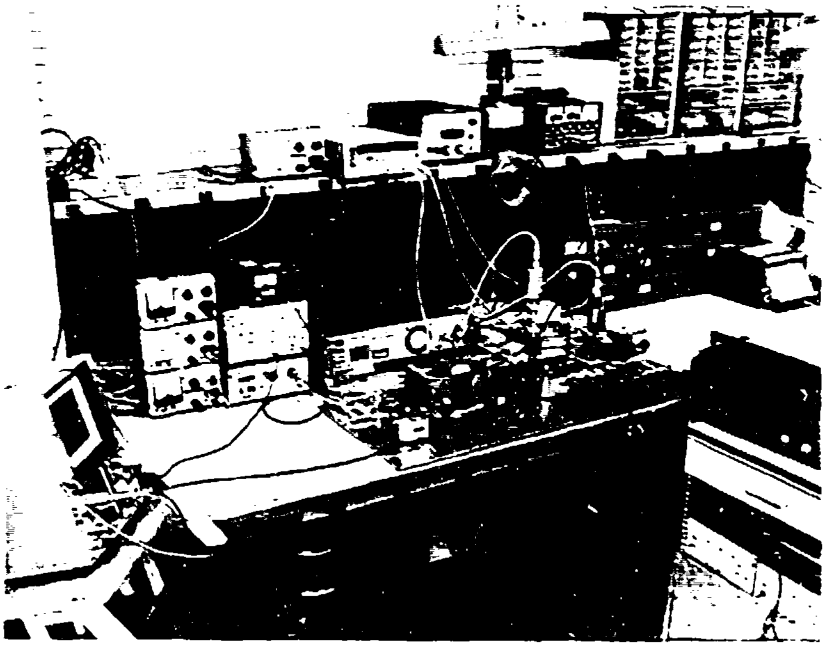

Figure 2. Photograph of the Measurement System.

The DUT consisted of a single-stage GaAs FET (or HEMT) low-noise amplifier that incorporated the discrete device in a test fixture; the amplifier was tuned for low noise and high gain at the center frequency of the microwave pulses. The input return loss at that frequency for a small signal was typically greater than 6 dB (i.e., 75% of the power was absorbed), but for microwave pulses greater than about 25 dBm, the percentage of power absorbed usually decreased because of large-signal effects.

The DUT was dc biased for low-noise operation by means of voltage supplies having automatic protection circuitry to shut them down when a preset current limit is exceeded. We set the gate-source current limit at 20 mA and the drain-source current limit at 50 mA. To test the effect of bias on burnout threshold, some measurements were made with the voltage supplies disconnected, while others were made with a 2-kW current-limiting resistor in series with the gate.

The standard testing sequence was as follows. First, ten manually triggered pulses were applied at a "safe" power level of about 29 dBm, then the DUT noise figure was measured to check for degradation in the DUT. The power was then increased by 1 dB to about 30 dBm, and ten manually triggered pulses were again applied, followed by another noise figure measurement. This procedure was continued, with the pulsed power input to the DUT being

increased in 1-dB steps and the noise figure being checked for degradation after each set of ten pulses. Typically, no degradation was observed until, upon one "burnout" pulse, the dc drain and gate current rose and the noise figure increased (by 0.1 to 3 dB or more). After the burnout pulse, either the pulsing was continued at the same power level (to test for further degradation), or the testing was terminated (if it was desired to inspect the damage with a scanning electron microscope).

The testing sequence above was modeled on that of [1,2]. It has been suggested [6] that the lower-power pulses in this testing sequence may weaken the device, and hence lower the burnout threshold. To test this hypothesis, we tried a different testing sequence on a few devices. In this testing sequence no lower-power pulses were applied; instead, a power level approximately 2 dB higher than the average damage threshold determined for similar devices was used from the start, and pulses were applied until burnout occurred. Our results suggest that any weakening effect is minor, lowering the burnout threshold by only 1 or 2 dB.

It has also been suggested that the burnout threshold may depend on the frequency content of the microwave power. To test this hypothesis, some measurements were made using two tones of equal amplitude, one at 7.9 GHz and one at 8 GHz. Other measurements used amplified white noise, which was band limited from 7.95 to 8.05 GHz. For both situations, our results indicate that the burnout threshold is lowered by a small but statistically significant amount. This lowering of the burnout threshold might not be observed for a single device, but the average burnout threshold for many (≥ 10) devices was lowered by a small amount.

Our measurements of the temperature dependence of burnout used a different procedure. Because this temperature dependence was expected to be small, it was desirable to eliminate the statistical variation of burnout power among devices of the same type. Hence, both pulse power and temperature were varied for a given device in a way designed to determine whether that device is more susceptible to burnout at a high or a low temperature. Two temperatures were used: 95 and -20 C. The devices were expected to be less vulnerable at the lower temperature than at the higher temperature, so the pulsing sequence was begun with ten pulses at the low temperature at a power level of 32 dBm (i.e., at a level where the device was not likely to burn out). The DUT was then warmed to 95 C and pulsed ten times at either 32, 31, or 30 dBm. After the DUT was cooled it was pulsed ten times at 33 dBm, and so on, until burnout occurred. The results show that the burnout threshold is about 2 dB lower at 95 C than at 20 C; this temperature dependence is similar to that observed in a previous investigation [2], where cw power was used to burn the devices out.

III. RESULTS

Table 1 gives the physical characteristics of the GaAs FETs and HEMTs tested. All of the devices listed, with the exception of GaAs FETs A and G, are available commercially as discrete devices. GaAs FET A is used by the manufacturer in their own millimeter-wave products, but it was obtained from the manufacturer in chip form for these measurements. GaAs FET G, obtained from the manufacturer as the active device in a modular amplifier, was tested as received to verify the burnout threshold reported for it by McAdoo et al. [6].

Table 1. GaAs FET and HEMT Physical Characteristics

Device	Type	Gate Length, μm	Total Gate Width, μm	Number of Gate Fingers
B	GaAs FET	0.3	280	4
C	GaAs FET	0.3	280	4
D	GaAs FET	0.5	250	2
E	GaAs FET	0.5	280	4
F	GaAs FET	0.3	200	4
G	GaAs FET	0.8	800	4
H	GaAs FET	0.5	400	4
J	HEMT	0.5	280	4
K	HEMT	0.3	200	4
L	HEMT	0.5	300	4
M	HEMT	0.5	300	4

For the standard test procedure described above, the burnout thresholds measured are given in Table 2. The results are reported in terms of the incident power on the DUT instead of the absorbed power, since the incident power is the controlled variable. The burnout thresholds for GaAs FETs are similar in magnitude to those reported in [1-5]. Three of the device types tested had greater than a 10-W average burnout threshold for 100-ns pulses.

The devices with shorter gate length or width tend to have lower burnout thresholds than do devices with longer gate length or width. Some unknown factors, most likely related to materials or processing, also strongly influence burnout threshold, as evidenced by the wide variation in burnout threshold found for a given device type. Device D, for example, has nearly a 10:1 variation in burnout threshold for the 45 devices measured; however, the variation within any single processing lot is usually less than 2:1. All the type-D devices measured with burnout thresholds exceeding 15 W were from one lot, while all the type-D

devices with burnout thresholds less than 3 W were from another. This variation among processing lots argues that processing and materials can strongly influence the burnout threshold without significantly affecting the microwave performance.

In contrast to the GaAs FETs, all of the HEMTs tested had burnout thresholds that were less than 10 W for 100–ns pulses. The HEMTs had burnout thresholds similar to those of some of the weaker GaAs FETs tested, but no HEMTs were as rugged as the stronger GaAs FETs. Nevertheless, HEMTs are desirable for many applications, because they offer microwave noise figures and associated gains unobtainable with GaAs FETs.

Table 2. GaAs FET and HEMT Burnout Thresholds
(using 1–db steps in power with 10 pulses per power level)

Device	Pulse Length, ns	Range of Burnout Thresholds, W	Average Burnout Threshold, W	Number of Devices Tested
A	100	4.8 - 1.3	2.7	5
B	200	4.1 - 3.7	3.9	3
B	20	26.0 - 25.8	25.9	3
B	10	31.0 - 29.3	30.1	3
C	100	15.1 - 13.8	13.9	3
D	100	20.4 - 2.1	7.5	45
E	100	21.4 - 14.4	18.3	3
F	20	15.7	15.7	2
F	10	12.7 - 9.8	11.2	2
H	100	17.0 - 16.3	16.7	2
J	100	7.0 - 2.1	3.8	10
K	20	11.0 - 6.3	8.0	4
K	5	25.2 -17.5	20.6	4
K	2	41.3 - 28.3	33.3	4
L	100	9.0 - 4.1	7.2	4
L	5	28.2 - 21.2	25.3	3
M	100	5.9 - 2.6	4.6	7

The burnout threshold of GaAs FET G agreed with the burnout threshold reported by McAdoo [6]. Note that GaAs FET G is a relatively large device, having a gate width of 800 μm, and is therefore not typical of most of the devices we or other investigators measured. This particular device was chosen because it was one of the device types that McAdoo chose to study. The other device types studied by McAdoo were not available. For this test we also used McAdoo's procedure of one pulse per power level, with 6–dB steps between power levels. However, our test frequency differed from McAdoo's. Because we did not have a TWT with

an output power greater than 10 W at 9 GHz, we used a frequency of 6 GHz. The amplifier tested was a 2 to 6-GHz amplifier, so our tests used an in-band frequency; McAdoo's tests used the out-of-band frequency of 9 GHz. Despite this difference, our results are nearly identical to those of McAdoo: the burnout threshold we measured is 33 W average for three devices, while McAdoo reported 31 W average for three devices.

Because the burnout threshold for GaAs FET G, for a 100-ns pulse length, is significantly higher than that of any other device we measured, we suggest that the devices McAdoo tested have higher burnout thresholds because they have relatively larger gate widths. This is corroborated by the fact that all the devices tested by McAdoo had gate widths greater than 500 μm, while the devices tested in this investigation (with the exception of device G) and by others [1-5] usually had gate widths of 300 μm or less. Because low-noise devices for frequencies above X-band nearly always have gate widths of 300 μm or less, the device types McAdoo tested would not be expected to be used in state-of-the-art front-end amplifiers.

Another reason for the high burnout thresholds reported in [6] is the testing procedure, as suggested in that reference itself. McAdoo used only one pulse per power level, while devices tested with our procedure of ten pulses per power level burned out only 37% of the time on the first pulse at a given power level (Figure 3). A device that would have burned out at a given power level on other than the first pulse using our procedure would not burn out at that power level using McAdoo's procedure, but it would have had an apparent burnout threshold of at least 6 dB higher.

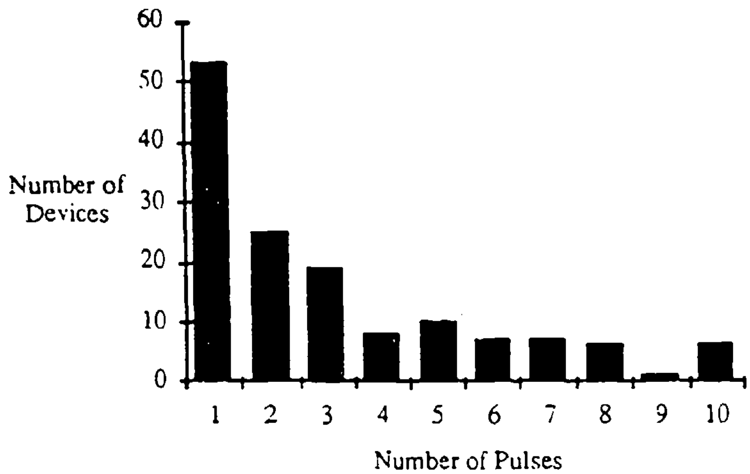

Figure 3. Number of Devices Burned Out vs. Number of Pulses at a Given Power Level.

As noted above, without having previously applied any lower-power pulses, we tested a few devices with pulses whose power was 2 dB above the burnout threshold determined by our standard testing sequence. If the accumulation of lower-power pulses in our sequence substantially weakens the devices, those devices with no prior history of exposure should not burn out immediately upon exposure to power levels only slightly above the average burnout threshold as determined by our technique. Our results suggest that any cumulative weakening effect is perhaps only 1 or 2 dB at most, since out of six devices tested, four failed on the first pulse, one failed on the second, and one on the third. Hence the burnout threshold as determined by our testing sequence of closely incremented power steps is more accurate than the threshold determined by the procedure in [6], where single pulses at 6–dB increments were used.

The tests of the other factors influencing burnout threshold, i.e., the temperature, bias condition and frequency content of the microwave power, were all performed on GaAs FET D. Because of the wide variation in burnout threshold among lots, each test involved only one lot.

We found that the burnout threshold at 95 C is lower than the burnout threshold at -20 C by between 1 and 3 dB. Only six devices were tested for their temperature sensitivity, so more-precise esimates of temperature sensitivity cannot be made. Note that the temperature dependence found is similar to that found in [2], where the devices were overstressed with cw power.

For the 11 devices measured, the presence or absence of bias did not affect the burnout threshold in a statistically significant way. This is not surprising, since the microwave ac voltage is much larger in magnitude than the dc biasing voltage. For the 14 devices measured, the addition of a current-limiting resistor in the gate appeared to lower the burnout threshold, since the average burnout threshold was $5.5 + 0.8$ W with the gate resistor (compared to $7.5 + 1$W without it) for 14 devices measured. This small effect probably resulted because the gate resistor limited the dc current through the gate, thereby affecting the large-signal microwave impedance of the gate so as to increase the absorbed power.

The use of two tones or band-limited white noise lowered the burnout threshold by a small but statistically significant amount. That is, a lower burnout threshold might not be observed in a single device, but the average burnout threshold for a statistically significant sampling of devices (≥ 10) would be lower by a small amount. Fifteen devices burned out by a single tone had an average burnout threshold of $6.6 + 0.3$ W, 10 devices burned out by two tones had an average burnout threshold of $5.5 + 0.6$ W, and 11 devices burned out by noise had an average burnout threshold of $5.3 + 0.4$ W. This decrease in threshold can be understood from the following argument.

Two tones or band-limited white noise can be modeled as a single tone that is amplitude modulated. This amplitude modulation is sinusoidal for the two tone, while random, band-limited modulation is used to simulate band-limited white noise. A single tone has the same voltage peak with every cycle, whereas the amplitude modulation makes the voltage peak vary from cycle to cycle — sometimes less, sometimes more than the single tone for the same average power. The maximum height of the varying voltage peaks was limited by the saturated output power (approximately 9.5 W) of the TWT amplifier. Whatever process occurs at the voltage peak (e.g. avalanche breakdown), it is apparently a strong enough function of the height of the peak voltage to make less frequent, but higher, voltage peaks more conducive to burnout than moderate-height voltage peaks that occur every cycle.

IV. BURNOUT CHARACTERISTICS

The initial burnout pulse always caused a low-resistance (< 1000 Ω) ohmic contact to form between the gate and the source, with an ohmic contact occasionally forming between the drain and gate as well. Although the effect on the microwave performance of the burnout pulse varied widely, the most common effect was a decrease ranging from 0.1 to 3.0 dB in the small-signal gain and an increase ranging from 0.1 to 3.0 dB in the noise figure. This effect can be related to the physical characteristics of the burnout, since the most common effect was a localized region of damage between the gate and source near the input to one gate finger (Figure 4).

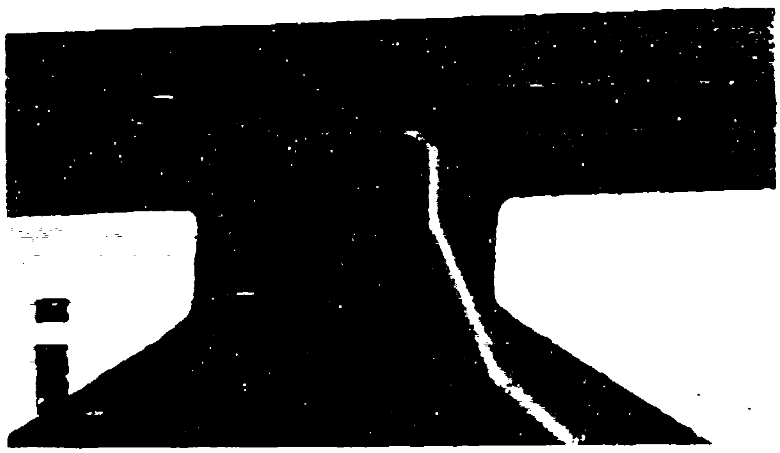

Figure 4. Type-B GaAs FET Damaged by Multiple Microwave Pulses. The location of the damage at the gate feed is typical for most device types.

This damaged region can take the one associated gate finger out of operation without having a major effect on the other gate fingers, resulting in the 0.1 to 3-dB degradation observed. However, if this low-resistance contact makes it impossible to bias the gate to the proper voltage, because of an inadequate dc gate supply (at least several milliamperes of current), the performance is substantially degraded. Usually, additional pulses following the burnout pulse at the same power level reduce the gate-to-source resistance, further degrading

the microwave performance. The gate-to-source resistance usually decreased to the point that the 20-mA current available from our supply was inadequate to bias the device after 1 to 10 additional pulses. When this stage of burnout degradation is reached, the device can be considered completely nonfunctional, since an unbiased amplifier has loss rather than gain.

The physical appearance of the damage has been described by previous investigators. Generally, there is erosion of the source metalization (Figure 5); this erosion is seen in the subsurface channel as surface uneveness in the channel region, or as a pit formed in the channel (Figure 6).

Figure 5. Type-D GaAs FET Damaged by a Microwave Pulse. Note the erosion of the source metalization.

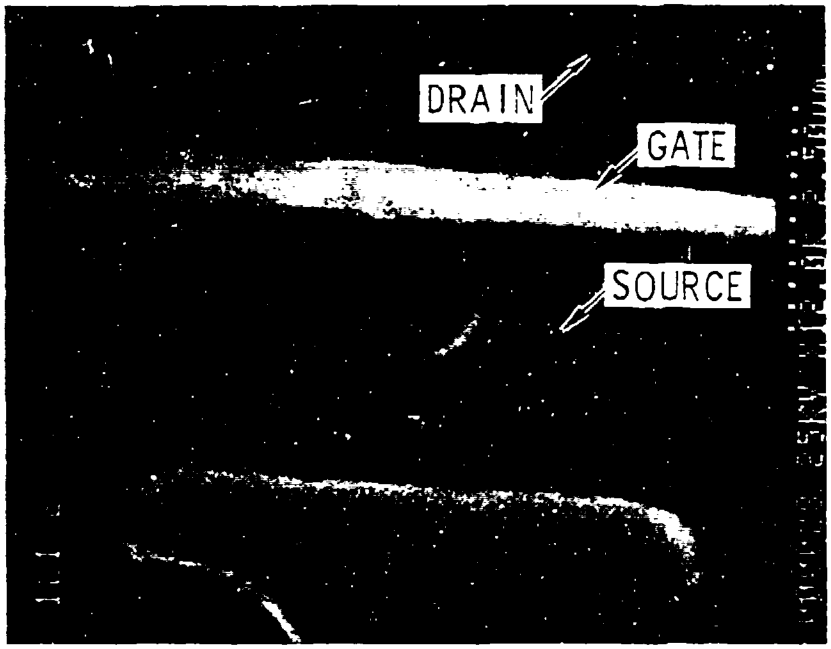

Figure 6. Type-A GaAs FET Damaged by a Microwave Pulse. Note the pit in the gate-source channel.

V. CONCLUSION

A variety of state-of-the-art, commercially available, low-noise GaAs FETs and HEMTs have been tested to determine their burnout thresholds in response to microwave pulses. Typical burnout thresholds are between 2 and 20 W for 100-ns pulses and up to several tens of watts for pulses 10 ns or shorter. A variation of the device temperature and bias and the frequency content of the microwave input caused small changes of about 1 or 2 dB in burnout threshold.

In contrast to the results presented in [6], no burnout thresholds in the hundreds of watts were observed. The burnout threshold for device type G agreed with that reported in [6], indicating that the difference in results for other types of devices is caused not by experimental error, but rather by a different choice of devices and test procedures.

The investigators in [6] used a test procedure that applied single pulses that were 6 dB apart, and the devices tested were of relatively large dimension (gate widths of approximately 800 μm). This test procedure allowed for large errors in the determination of the burnout threshold. Furthermore, because of their relatively large dimensions, these devices have an inferior noise figure and thus are not expected to be used as front-end elements.

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